EFFECTS OF GROUND-WATER PUMPING ON STREAMFLOW:

LEGAL AND HYDROLOGIC ASPECTS

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ABSTRACT

Surface-water-ground-water relations and the effect of ground-water pumping on streamflow are hydrologic issues that normally are not properly understood by the non-technical sector (legal, adjudication, regulatory, etc.). Where water rights distinguish between surface water that is appropriable and ground water that is available for reasonable use by land owners on their land, conflicts arise where ground-water pumping reduces streamflow. For the latter, legal attempts' have been made to classify ground water into percolating water, underground streams, and subflow where percolating water was considered as ground water and the other two as surface water for water rights purposes. These classifications, of course, have no basis in hydrologic fact. Also, "Bright lines" have been introduced to distinguish between zones where wells pull a lot of water out of streams and legally pump surface water, and where they do not pull much water out of streams and legally pump ground water. In Arizona, arbitrary percentages for surface and ground water and periods of pumping were selected (50% - 90 day rule), and the locations of the lines were based on analytical solutions with very limited applicability. Hydrologically, surface and ground water form one continuum, with surface water being above ground and ground water being in geologic formations of different hydraulic conductivity. There also can be underground water in the vadose zone. The main issue in this "conflict" is how ground-water pumping affects streamflow. Ground-water flow models have shown, that, generally, a lowering of ground-water levels will increase stream seepage losses and, hence, decrease streamflow, where ground-water levels are relatively high and ground-water flow is mostly lateral and gradient (slope of water table) controlled, but not where ground water is already relatively deep and seepage flow is mainly downward and gravity controlled. For clean channels, maximum seepage is already approached when ground-water levels have dropped to a depth below the stream that is equal to about two times the width of the stream. Where channel perimeters are covered with a layer of sediment or other clogging material, the flow below the channel bottom becomes unsaturated if the ground-water level drops to about 3 feet below the bottom. At this point, further lowering of ground-water levels will not increase seepage flows. Ground-water depletion by pumping can enhance "capture" of water by aquifers through increased seepage from streams, reduced seepage into streams, and reduced evapotranspiration by phreatophytes and other vegetation. Analytical solutions that have been developed in the past to calculate the effect of ground-water pumping on stream flow were based on the assumption of horizontal flow in the aquifer and, therefore, fail where ground-water levels and bedrock are relatively deep and vertical (gravity) flow components dominate. Computer models like MODFLOW can closely simulate regional or basin wide systems of streams, aquifers, wells and other discharges, recharges, capture, and heterogeneities on a three-dimensional basis. Predictions from such models of how ground-water pumping affects streamflows can then be used to develop integrated water management schemes and to adjudicate remaining conflicts between surface and ground-water users and environmental concerns. This will require close cooperation between the legal/regulatory and hydrologic/engineering professions.

INTRODUCTION

The distinction between surface water and ground water seems very simple: surface water is above the ground, you can see it and you can float a stick on it; ground water is below the ground, you cannot see it and you cannot float a stick on it. However, surface water can become ground water and vice versa, and this is where the problems begin because some people use surface water and others use ground water and have a water right to one or the other, or both. Conflicts arise when the use of one affects the availability of the other, and when the sum total of water rights exceeds the renewable supply. The courts and legislators have always struggled with water rights issues and still do. Some states have separate water-right structures for surface water and ground water, and have developed intricate schemes for classifying water to where some ground water legally becomes surface water! Other states consider surface water and ground water one continuum and have a uniform code so that water right holders can get their water from streams or wells or both.

The main issue is a technical one—how streamflow affects ground water and how ground-water pumping affects streamflow. Various approaches can be used to assess the latter, including an analysis of how depth to ground water affects stream seepage losses and, hence, streamflow, and how lowering of ground-water levels[3] by pumping or for other reasons increases stream seepage losses and, hence, decreases streamflow. Different scenarios of hydrogeologic conditions[4] can be considered. Long-term effects of how ground-water pumping affects streamflow are more difficult to predict. Such effects are best estimated with ground-water flow models[5]. The results can then be used as the basis for better water resources management and adjudication of surface and ground-water rights that are based on sound hydrologic principles.

THE LEGAL SNAKE PIT

There is no better illustration of the legal quagmire created by separate codes for surface-water rights and ground-water rights than the state of Arizona. In Arizona, the prior appropriation doctrine[6] governs the rights to the surface waters of rivers and streams. Prior appropriation has three critical elements: 1) the principle that the first-in-time is the first-in-right, 2) a fixed maximum quantity is allocated, and 3) the right may be lost through abandonment or forfeiture through non-use. Ground-water pumping is governed by the "reasonable use" doctrine[7]. This doctrine allows land-owners to pump any "reasonable" quantity of water for use on the overlying parcel. The "reasonable use" right involves neither a fixed allocation nor a priority date. Water cannot be exported for use outside the overlying land. To enable regulatory control of ground water under the reasonable use doctrine, landowners legally are considered to only own the use of the ground water but not the molecules! A typical reasonable use is agricultural irrigation.

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[3]The ground-water level or water table, as it is some times known, is the upper boundary of a saturated ground-water flow system or aquifer. Ground water is at above-atmospheric pressure. The water table is at atmospheric pressure.

[4]Hydrogeologic conditions principally focus on ground-water conditions such as water tables and aquifers characteristics.

[5]Ground-water flow models are mathematical models solved on computers that simulate ground-water flow.

[6]For a general discussion of prior appropriation, see David H. Getches, Water Law in a Nutshell, 74-77 (2nd ed. 1990)

[7]*Id.* at *supra* note 5 at 253-54.

Whenever there is a conflict produced by the interactions of ground and surface waters, the Arizona Supreme Court turns to the bookshelf and pulls down a dusty, worn copy of a 1912 treatise entitled *The Law of Irrigation and Water Rights* written by Clesson S. Kinney[8]. Kinney, a Utah attorney and not a hydrologist, divided ground-water flow into courses of *known* and *unknown* channels of water. He further subdivided the known channel waters into *independent* and *dependent*, with the former being uninfluenced by streams and the latter constituting "subflow" of streams. One form of *independent* water he referred to as "tributary ground water." This was ground water that had "not yet reached the channels of the water courses to which they are tributary". Thus Kinney created a dichotomy of ground waters that interact with surface waters—"subflow" and "tributary ground water"—and set the stage for the chaos that followed.

In 1931, in an appeal decision by the Arizona Supreme Court entitled *Maricopa County Municipal Water Conservation District No. One v. Southwest Cotton*[9] (called *Southwest Cotton* for short), it was decided that Kinney's "subflow" (although ground water) was appropriable like surface water but that all other forms of Kinney's ground waters were not. To the *Southwest Cotton* Court, "subflow" is "waters that slowly find their way through the sand and gravel [of] the bed of the stream, or [through] lands under or immediately adjacent to the stream ...."[10] – hardly a precise definition upon which an engineer would hang his hat, let alone his professional reputation!

Because a watershed may have literally thousands of users whose rights are contingent upon the date of the original diversion and upon continued use of the water, and because over the years the dates and uses have become obfuscated, states have instituted a litigation procedure called an adjudication to restate the priority and scope of those rights. For Arizona, the Gila River General Adjudication began in 1974[11]. In 1988, Trial Judge Goodfarb[12] ruled that certain wells were within the scope of the Adjudication—that is, they were pumping appropriable (i.e., surface) water. He did not rely on Kinney or "subflow". His criterion, which became known as the 50-90 rule, stated that ground water is appropriable if it is determined that

"As to wells located in or close to [the] younger alluvium, the volume of stream depletion would reach 50 percent or more of the total volume pumped during one growing season for agricultural wells or during atypical cycle of pumpage for industrial, municipal, mining, or other uses, assuming in all instances and for all types of use that the period of withdrawal is equivalent to 90 days of continuous pumping for purposes of technical calculation.[13]"

Although Judge Goodfarb's definition of appropriable ground water seems arbitrary (why not 40% or 60% in 80 days or a 100 days), at least it was quantifiable. Indeed, Judge Goodfarb instructed the Arizona Department of Water Resources (ADWR) to produce a hydrographic survey that delineated the 50-90 boundaries for a portion of the Gila River General Adjudication

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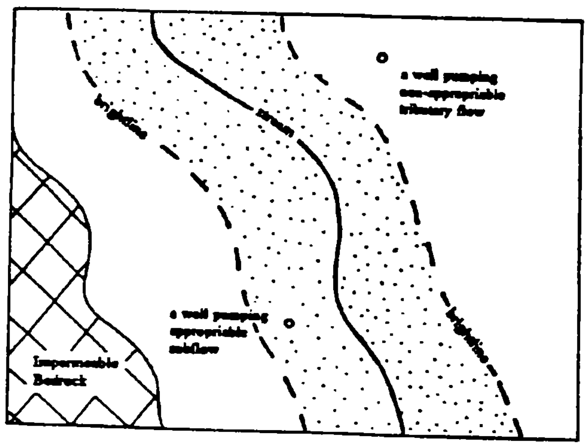
[8]Citing 2 Clesson S. Kinney, The Law of Irrigation and Water Rights §1161. at 2106 (2nd ed. 1912)
[9]39 Ariz 65, 4 P.2d 369 (1931).
[10]*Id.* at 96.
[11]The Arizona General Adjudication of Water Rights statues are set forth in ARIZ. REV.STAT. ANN. §§ 45-251 to 260 (4).
[12]*In Re* the General Adjudication of All Rights to the Water in the Gila River System and Source, Nos. W-1 through W-4, 15 Indian L. Rep. (Am. Indian law. Training Program) 5099, 5100 (Maricopa Super. Ct. October 1988).
[13]*Id.* at 5102.

area[14]. These boundaries were referred to as "bright-lines" (see Figure 1). Any well within or on the bright-line boundary is pumping appropriable ground water, any well outside it is not. ADWR used an analysis developed by Jenkins[15] to determine bright-lines for the San Pedro River, a tributary of the Gila River, as a test of the rule. Ignoring the arbitrary nature of the 50-90 rule, there were still five other major problems with the rule: four technical and one legal. First, the 50-90 rule completely disregards the actual volume depleted — it uses the ratio of stream

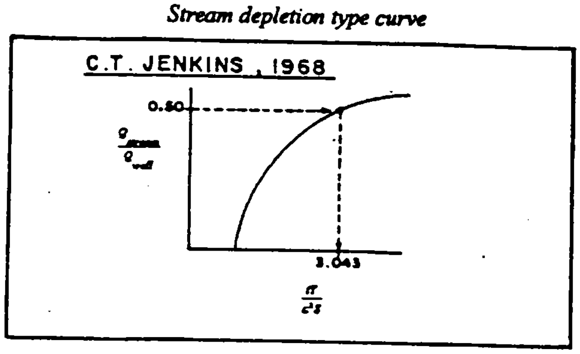
Figure 1:How the brightlines would have worked.



[14]ADWR, Preliminary Hydrographic Survey Report for the San Pedro River Watershed, Vol. 1, (1990).

[15]Jenkins used a stream-depletion type curve to determine the distance a from a stream to a bright-line. For a 50% allowable stream depletion, the type curve gives the value 3.043. Thus $\frac{tT}{a^2S} = 3.043$, and if t is 90 days and the transmissivity T (see fn. 68) and storativity S (see fn. 69) are known from field studies, the distance a can be calculated (For the assumptions and derivation of the stream-depletion type curve see Jenkins, C.T., Techniques for Computing Rate and Volume of Stream Depletion by Wells, Ground Water, 6(2), Pp.37-46, 1968).

Stream depletion type curve



depletion volume to well pumpage volume. For example,one well may be pumping 51% from stream depletion while pumping at the rate of 0.5 cubic feet per second (cfs). Another well may be pumping only 49% from stream depletion while pumping at the rate of 10 cfs. The former would be included in the adjudication, the latter would not—yet there is no question that the 10 cfs well would have a far greater impact on the river. Second, the Jenkins' analysis treats each well as a separate entity and ignores interactions between wells that exacerbate the impacts on the river[16]. Third, the Jenkins' method which the ADWR used to calculate the "bright lines" applies only to streams that fully penetrate the aquifer (all the way down to bedrock—even if it is at 1000 feet) and to purely horizontal flow in the aquifer. This may be reasonable for situations of shallow aquifers with deep streams above shallow bedrock, but not where the ground-water

Figure 2: Constant head and fully penetrating assumption

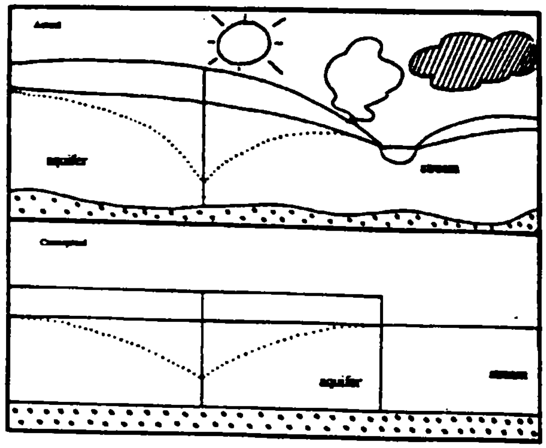


table is 300 feet deep and depth to bedrock is 1000 feet. In those cases, Jenkins' analysis greatly overestimate the amount of surface water that is drawn into the aquifer by ground-water pumping! Fourth, Jenkins' analysis assumes complete recovery of ground-water levels between irrigation seasons or other pumping episodes thereby ignoring the long term effects of regional overdrafts. Fifth, and finally, the 50-90 rule ignored "subflow".

In 1993, the Arizona Supreme Court, reaching back to its volume of Kinney through the application of *Southwest Cotton*, threw out the 50-90 rule[17]. Among other things, the Court argued that the 50-90 rule, based on a volume-time test, did not define "subflow" and remanded Trial Judge Goodfarb to define it. In July of 1994, after nearly a year of evidentiary hearings, Judge Goodfarb issued a definition of "subflow". Judge Goodfarb had been hamstrung by the Court's overreaction to the time-volume issue. The Court ruled out the use of volume ratios and

[16]When a well is pumped, a conical decline in the ground-water levels forms around the well. This conical decline is called the cone of depression. If there are a number of wells in close proximity to one another, their cones of depresions interact to produce greater impacts on ground-water levels and the river.

[17]175 Ariz 382, 857 P.2d 1236 (1993).

time in the "subflow" definition, arguing that the 1931 *Southwest Cotton* Court (i.e. Kinney) didn't use them, and that therefore Judge Goodfarb can't use them. This, of course, prevented the use of any modern hydrologic principles in defining "subflow"[18] . Perhaps it is just as well for subflow to be a legal concept and not a hydrologic one. Judge Goodfarb's 1994 definition of "subflow" was strictly geologic—ground waters within the saturated younger alluvium[19]. Ironically (or perhaps by intention), when the boundaries of the saturated younger alluvium are plotted with the old "bright lines", they nearly overlap! The issue is not over—Judge Goodfarb's definition of "subflow" is in the appeal process again. As of the writing of this paper, a decision by the Arizona Supreme Court is still pending, but could be years away.

The Courts dependence on *Southwest Cotton* has an interesting irony. On appeal, Southwest Cotton had argued that they were pumping "subflow", forcing the *Southwest Cotton* Court to define it[20] and to provide a test—does drawing off the subsurface water tend to diminish appreciably and directly the flow of the surface stream? – if it does, that subsurface water is subject to appropriation rules.[21] The *Southwest Cotton* Court concluded that there was no evidence that Southwest Cotton's pumping directly or appreciably diminish the flow in the river.[22] Application of modern hydrologic principles and techniques would have shown that ground-water pumping near the banks of the Agua Fria river would have indeed directly and appreciably affected the stream and, in all likelihood, the appeal would have been upheld. Arizona might not have been saddled with a bifurcated ground and surface water law, and subflow might have been relegated to a pseudo-geologic legal definition of little or no consequence.

The Arizona Supreme Court thought its role in the 1993 decision was to interpret *Southwest Cotton*, and not to correct or improve it. However, one of Courts interpretations contained a seed of hydrologic sanity... [If] a well's cone of depression has expanded to the point that it intersects a stream bed, it must certainly be pumping subflow... [23] ". Judge Goodfarb expanded on the Court's interpretation and concluded that a well outside the "subflow" area will be subject to the adjudication (i.e. it will be pumping appropriable water) if the "cone of depression" caused by its pumping has now extended to a point where it reaches and adjacent subflow zone, and by continual pumping will cause a loss of such subflow as to affect the quantity of the stream[24]. Furthermore, the Court traditionally had held that there could never be "subflow" beneath ephemeral streams[25] , but Judge Goodfarb ruled that if the ephemeralization was due to wells

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[18]See ADWR, Tech. Assessment of the Ariz. Sup. Ct. Interlocutory Appeal Issue No. 2 Opinion, Dec. 15, 1993.
[19]Goodfarb uses a definition for the younger alluvium as ...unconsolidated sand and gravel deposited within the [stream] channel course of perennial or intermittent streams by the stream itself... *See In re* the General Adjudication of All Rights to Use Water in the Gila River System and Sources, Maricopa County Superior Court, July 5, Pg. 24, 1994.
[20]39 Ariz. at 96-97, 4 P.2d 369 (1931).
[21]*Id.* at 380-381.
[22]*Id.* at 99, 106.
[23]175 Ariz. at 391, 857 P.2d at 1245.
[24]*See In re* the General Adjudication of All Rights to Use Water in the Gila River System and Sources, Maricopa County Superior Court, July 5, at 66, 1994.
[25]Ariz. Rev. Code § 3280 (1928).

pumping, those wells were pumping "subflow"[26]. It may not matter how "subflow" is defined if the Court upholds Judge Goodfarb's findings dealing with the cone of depression.

Having the Courts spend an inordinate amount of time trying to define terms such as "subflow" or "tributary ground water" will only perpetuate the bifurcated ground and surface water systems. What must be avoided is a further bifurcation that would lead the Courts to believe that if a well pumps water directly from the stream it is pumping "subflow" and is therefore subject to the appropriation doctrine. On the other hand, if a well intercepts water that would arrive at the stream, it is pumping "tributary ground water" and is subject to the "reasonable use" doctrine. In both of the cases, the cone off depression has intersected the stream. To the riparian tree, the aquatic critter, or the downstream user, both wells produce the same effect on the river—diminished flow!

The Court's adherence to the concept of "subflow" has created and exacerbated tensions between the State and the federal government. The federal reserved rights doctrine "will impose a completely different set of legal rules concerning the relation between ground and surface water"[27].

STEPPING THROUGH THE LEGALESE

To the hydrologist or engineer, the Arizona distinction of "subflow" as a special part of ground water is mind boggling to say the least. Ground water occurs as one continuum in strata of different hydraulic conductivity[28] and underlain by bedrock or other "impermeable" formation. Also, ground water may become surface water in some reaches of a stream, while surface water may become ground water in other reaches. In the desert regions of the Southwest, natural recharge of ground water from the land itself above it is very small; i.e., about 1% of precipitation or on the order of 1 mm/yr[29], and ground-water levels tend to be at considerable distance below streambeds. The main source of ground water and ground-water recharge then is seepage from losing streams[30] (ephemeral[31], intermittent[32] or perennial[33]) in valleys and on alluvial fans[34] or other upper elevations. The latter are called mountain-front recharge and consists primarily of seepage from streams coming out of the mountains and from rivulets and other surface runoff on the fans themselves. Under these conditions, essentially all ground water at one time was streamflow that seeped into the ground, then became "subflow" as it joined the

[26]*See In re* the General Adjudication of All Rights to Use Water in the Gila River System and Sources, Maricopa County Superior Court, July 5, at 36, 1994.

[27]Glennon and Maddock, In Search of Subflow: Arizona's Futile Effort to Separate Ground from Surface Water, Ariz Law Rev., 36 (3) at 610, 1994.

[28]Hydraulic conductivity or permeability express an aquifer's ability to transmit water through its pores.

[29]See Bouwer, H., Estimating and Enhancing Groundwater Recharge, In: Groundwater Recharge, M.L. Sharma, ed. A.A. Balkema, Rotterdam, The Netherlands, p. 1-9, 1989.

[30]In a losing stream, water infiltrates from the stream into the aquifer. The net effect over a reach of the river is a loss in stream flow.

[31]An ephemeral stream flows only after a storm event.

[32]An intermittent stream has flows in certain reaches but not in others and may flow only seasonally.

[33]A perennial stream flows all year long.

[34]An alluvial fan is a sand and gravel deposit at the mouth of mountain canyons or streams.

aquifer in the upper alluvium of the streambed or floodplain, and finally became "true" ground water as it moved deeper and away from the stream in response to natural ground-water movement and ground-water withdrawals such as pumping, evaporation, and uptake by phreatophytes[35] or riparian vegetation. So this raises the question: where does "subflow" end and "true" ground water begin? Is the transition sharp or gradual? Must "subflow" be legally divided into recent and old "subflow", or into upper, middle, and lower "subflow"? And what about ground-water in buried valleys or ancestral streambeds, is that deep "subflow"? Where ground-water levels are higher than water levels in streams, ground water will move into the streams to provide the base flow[36] for perennial and "gaining" streams[37], as for example, for portions of the Gila and San Pedro rivers. Should this base-flow portion of the surface water then be treated ase ground water and, rather than being appropriable like surface water, be subject to the reasonable use doctrine as applying to the ground water it was before seeping into the stream? To conserve legal symmetry, let the Court call this base-flow portion "superflow"!

In the past, other states have developed similar legal artifacts such as "percolating water and "underground streams". Legal terms such as "subflow", "percolating ground water", and "underground streams" defy precise scientific definition. This prompted Coogan[38] to write:

"The law - a formal set of rules by which society is ordered - seems to the physical scientist a strangely confusing and confused tool with which to define, even in a social context, the parameters and limits of a physical continuum. For example, on the basis of attorneys' briefs bolstered even by expert testimony, judges have legally defined "subterranean streams" and erected criteria for recognizing such streams that sound more like the rhetoric of Humpty Dumpty than a description of a body of water one could scoop up in a bucket, or upon which one could float a rubber raft."

Regardless of what the legal profession makes of it, relations between surface water and ground water and how withdrawal of one affects the other are hydrologic issues that can only be solved by hydrologic analyses and hydrologic specialists. As Coad[39] wrote:

"Engineers must take a leadership role. We shouldn't look to legislators, litigators, and economists to tell us what to do. They'll give us nontechnical solutions to technical problems. This will lead to chaos."

HYDROLOGIC ASPECTS

C. V. Theis[40] introduced the following fundamental ground-water principle:

[35]A phreatophyte is a plant whose roots extract ground water.
[36]Base flow is the return flow to a stream from the ground water.
[37]In a gaining stream, water infiltrates from the aquifer into the stream. The net effect over a reach of the river is an increase in streamflow.
[38]Coogan, H.A. 1975. Problems of groundwater rights in Ohio. Akron Law Rev. 9(1): 34-115.
[39]Coad, W. 1994. Ground Water Market Trends, Newsletter of the Association of Ground Water Scientists and Engineers. 5(11), p. 9.
[40]Charles V. Theis, The Source of Water Derived from Wells, Civ Engineering, May 1940, at 277.

"Under natural conditions ... previous to the development of wells, aquifers are in a state of approximate dynamic equilibrium. Discharge from wells is thus a new discharge superimposed upon a previous stable system, and must be balanced by an increase in the recharge of the aquifer, or by a decrease in the old natural discharge, or by loss of storage in the aquifer, or by a combination of these."

Thus prior to the development of wells, a regional ground-water system exists in a state of approximate dynamic equilibrium, and this equilibrium is maintained by a long-term balance between natural recharge and discharge processes[41]. Over the millennia, wet years when recharge exceeds discharge are balanced by dry years when discharge exceeds recharge. Since recharge to and discharge from the system are in balance, there is no change in ground-water storage. If R is the average recharge and D is the average discharge, the equilibrium condition is written:

$$R = D \qquad (1)$$

A schematic of predevelopment conditions for a ground-water basin in the dry Southwest is presented in Figure 3. Recharge to the basin primarily occurs from underflow in from other watersheds, losing streams, and mountain-front recharge. Discharge out of the basin occurs from underflow out to other watersheds, gaining streams, and evapotranspiration[42]. Discharge from wells, Q, is a new process imposed on a previously balanced ground-water system, and is balanced by a decrease in storage, ΔS, and/or some combination of an increase in recharge, $R+\Delta R$, and a decrease in natural discharge, $D-\Delta D$. Theis' principle requires a new equilibrium condition:

$$(R+\Delta R) - (D - \Delta D) + Q = \Delta S \qquad (2)$$

Since $R - D = 0$, Equation (2) can be expressed as:

$$\Delta R + \Delta D - Q = \Delta S \qquad (3)$$

The term ($\Delta R+\Delta D$) is called capture and is the sum of pumping-induced increased recharge plus pumping-induced decreased discharge[43]. Equation (3) states that the storage loss in a system equals the deficit between the discharge from wells and the capture. Capture comes from 1) increased infiltration from losing streams, 2) interception of water to gaining streams, and 3) reduction of evapotranspiration.

Equation (3) provides two important pieces of information:

1. If there are no sources of capture, *i.e.* $\Delta R+\Delta D = 0$, then all the water that the wells pump comes from storage loss, *i.e.* $Q = \Delta S$

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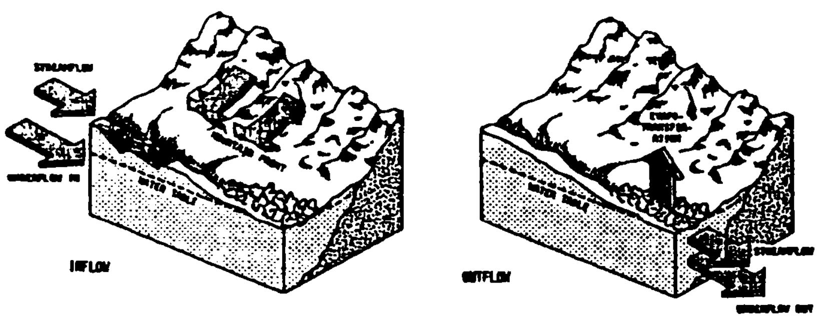
[41] Recharge processes occur when surface and subsurface waters flow into the aquifer, and discharge processes occur when ground waters flow out of an aquifer.

[42] Evapotranspiration is water lost to the atmosphere by evaporation from the soils and transpiration from plants.

[43] See Bredehoeft, John D., Stephen S. Papadopulos, and H. H. Cooper, Jr., Groundwater:The Water Budget Myth, in Science Basis of Water-Resources Management, 51, 53, National Research Council.

2. If a safe yield is defined as no increased storage loss, *i.e.* $\Delta S=0$, then the wells must be restricted to pump what they can capture, i.e. $Q=\Delta R+\Delta D$.

Figure 3: Recharge and discharge processes in a southwestern basin,(Anderson, Freethey and Tucci 1990)



During the initial stages of pumping, most water is withdrawn from storage because the lateral expanse of the cone of depression is initially small and sources of capture are unlikely to be disturbed. However, as pumping continues and the cone of depression expands, the growing zone of influence is more likely to intercept other sources of water.

STREAM CAPTURE

If the source of capture is a stream, four basic situations can be distinguished[44]

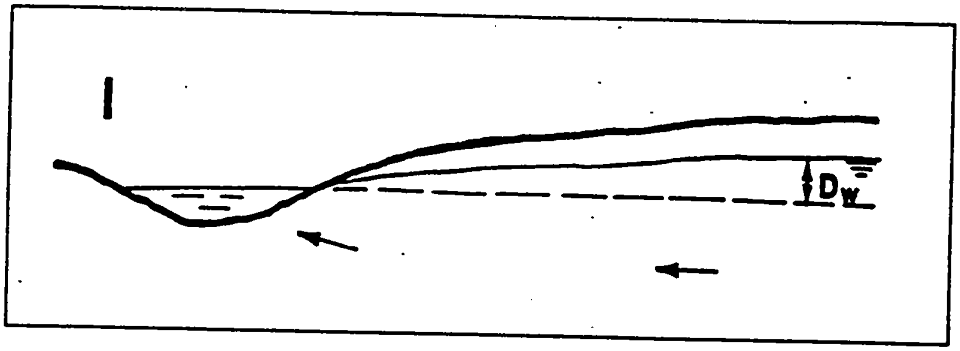
I. The stream is perennial and the channel and the stream bed are "clean" (no deposits of fine or organic material on the wetted perimeter). The ground-water table is above the water surface of the stream so that ground water moves into the stream and the stream is gaining (Figure 4). The (upper) aquifer is relatively uniform, unconfined[45], and underlain at some

[44] See Bouwer, H., Theory of Seepage from Open Channels, In: Advances in Hydroscience, Vol. 5, V.T. Chow (ed), Academic Press, New York, 121-172 (1969), and Bouwer, H., Groundwater Hydrology, McGraw-Hill, New York, N.Y., 480 pp. (1978).

[45] In an unconfined aquifer, the water table is at the upper boundary of the saturated ground-water flow system that is at atmospheric pressure. An aquifer with a water table is also called a water-table aquifer.

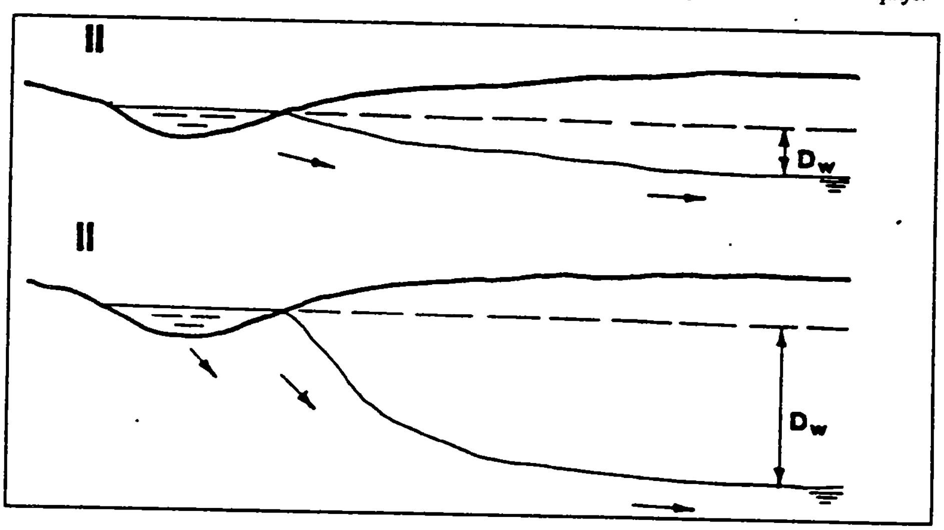
distance by an impermeable boundary like clay or rock, or very permeable boundary like gravel[46].

Figure 4: Case I: Shallow aquifer with a gaining stream



II. As Case I, but the ground-water table is below the water surface in the stream, causing water to seep out of the stream and into the aquifer (losing stream, Figure 5). Two situations are shown: a shallow water table with predominantly horizontal flow in the aquifer, and a deep water table with vertical flow dominating below the stream.

Figure 5: Case II: Losing stream hydraulically connected to the aquifer



III. As Case II, but the stream wetted perimeter is covered with a blanket of fine sand, silt, or clay, and possibly organic deposits (biofilm, benthic layer) called a clogging layer that restrict and control the seepage rate and cause underlying material to be unsaturated.

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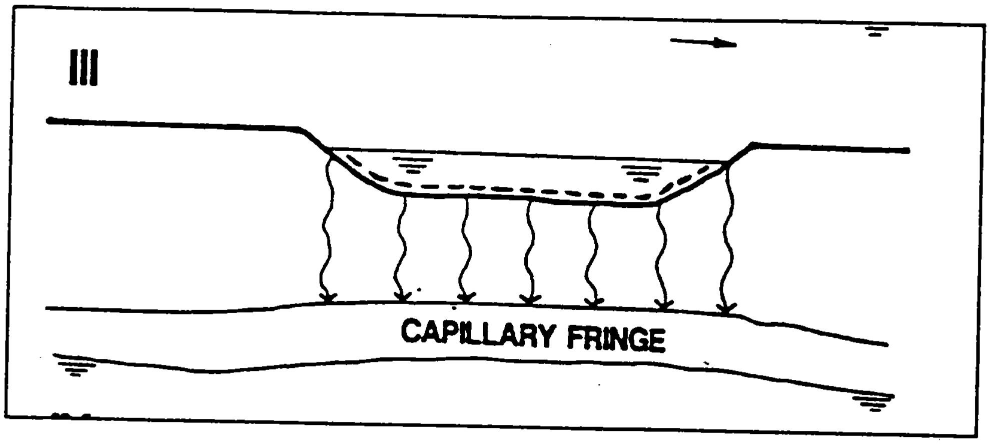
[46]As odd as it may seem, the impermeable boundary and the highly permeable boundary produce the same hydrologic effect – horizontal flow.

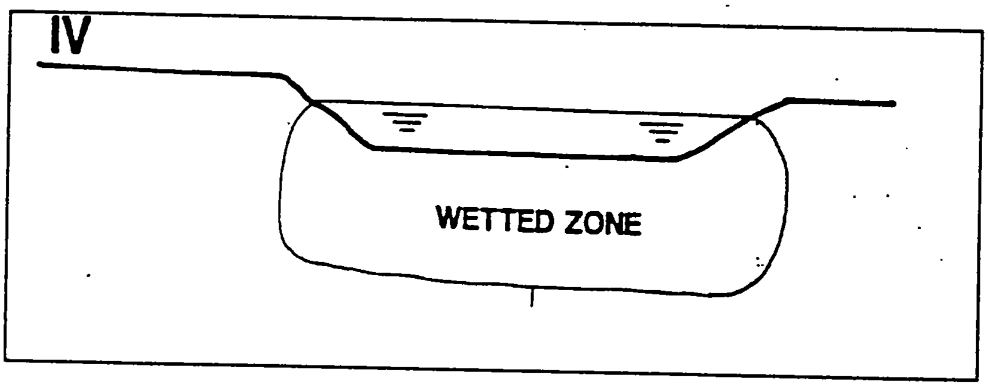
Seepage water then percolates down as unsaturated flow until it hits the capillary fringe[47] (Figure 6).

Figure 6: Case III: Unsaturated flow beneath a prennial stream with a clogging layer



IV. As Case II or III, but the stream is intermittent or ephemeral (Figure 7). The water table may be some distance below the wetting zone[48].

Figure 7: Case IV: Unsaturated infiltration flow beneath an ephemeral stream



PERENNIAL STREAMS

For Case I, seepage into the stream can be calculated on the basis of one-dimensional flow[49] if the lower boundary is impermeable and at, or not far below, the bottom of the channel so that the

[47]The capillary fringe is a small layer above the water table where the pressure is less than atmospheric but the layer is saturated.

[48]The wetting zone is a saturated or near saturated zone beneath the stream.

whole system is shallow and the ground-water flow predominantly horizontal[50]. If the impermeable boundary is deeper or the lower boundary is very permeable, vertical flow components become significant and the seepage flow system must be analyzed for two-dimensional flow[51]. For Case I there is a direct hydraulic connection between the ground water and the stream[52], ground water is tributary to the stream, and the rate of flow of ground water into the stream is directly proportional to the slope of the water table; i.e., the height D_W of the ground water table above the water level in the stream at some distance from the stream. If D_W is reduced by pumping ground water, the rate of seepage flow into the stream will decrease linearly with D_W. Since the ground water is tributary to the stream, there will then be "one cup of water less in the stream for each cup of water taken out of the aquifer." Thus, all ground-water extractions from an aquifer that is tributary to a stream capture waters that would have entered the stream. Accumulated streamflow then is reduced by the total amount of water withdrawn from the tributary aquifer. This capture is a reduction in discharge from the aquifer.

If the water table in Figure 4 away from the stream is sufficiently high to be within reach of plant roots (for example of deep rooted trees like salt cedar, mesquite, willow, cottonwood, or other "phreatophytes"), considerable amounts of water (often 1.5 feet to 7.5 feet per year) are lost from the ground water due to uptake by tree roots and subsequent transpiration from the leaves. When ground-water levels are lowered, this consumptive use or water "loss" decreases and may stop altogether when the water table drops below the root system and the trees begin to die[53]. Reduction in evapotranspiration is another form of capture and is a reduction in discharge.

If the duration and quantity of the ground-water withdrawals are large enough, water levels in the tributary aquifer will drop until eventually the water table will be at the same elevation of the water surface in the stream and the flow of ground water into the stream has stopped. At this point, the stream's base flow has become zero and the stream's flow is sustained only by surface runoff and possibly base flow from further upstream. When ground-water pumping is continued, ground-water tables drop below the water surface in the stream, water seeps from the stream into the aquifer, and the stream becomes a losing stream with diminishing stream flows (Case II, Figure 5). Ground-water pumping then draws water directly out of the stream, in contrast to ground-water pumping in gaining stream situations (Case I) where the pumping takes water out of the aquifer before it goes into the stream. For Case II, capture is in the form of increased recharge to the aquifer from the river.

If the water table in the losing stream situation is still relatively high and D_W is relatively small (Figure 5, top), the seepage losses from the stream will increase linearly with increasing D_W as caused by declining ground-water levels. However, as the water table continues to drop and D_W continues to increase, the seepage flow below the stream becomes increasingly downward and

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[49]One dimensional flow is in the horizontal direction, vertical flow. This type of flow in this type of ground-water system is sometimes call Dupuit-Forchheimer flow, See Bouwer, H., Groundwater Hydrology, McGraw-Hill, New York, N.Y., 480 pp. (1978).

[50]*Id.*

[51]Flow in both horizontal and vertical direction. See *Id.* and Bouwer, H., Theory of Seepage from Open Channels, In: Advances in Hydroscience, Vol. 5, V.T. Chow (ed), Academic Press, New York, 121-172 (1969).

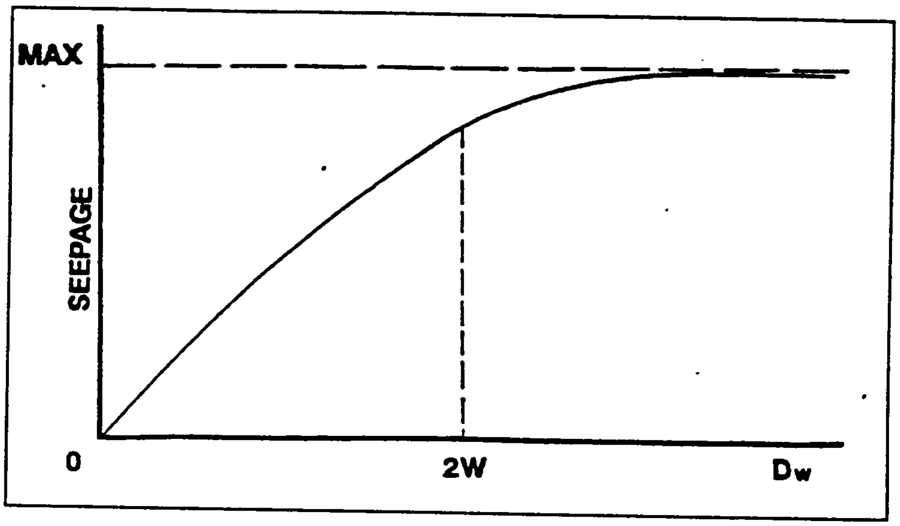
[52]Direct hydraulic connection requires that the water table or saturated zone intersects above the bottom of the stream bed.

[53]See Bouwer, H., Predicting Reduction in Water Losses from Open Channels by Phreatophyte Control, Water Resources Res., 11(1), pp. 96-101 (1975).

will be more and more controlled by gravity and not by the slope of the water table (Figure 5, bottom). Thus, if seepage losses from the stream is plotted against D_W, the curve (Figure 8) will be linear in the beginning (small D_W), but then become curvilinear and asymptotically approach the maximum seepage value obtained when the ground water is infinitely deep (D_W= 4)[54].

The turn-over from linear-like behavior to strictly non-linear behavior occurs when D_W is about twice the width of the stream[55]. The imaximum seepage rate from a stream occurs with vertical flow. If the value of D_W is greater than twice the stream width, the seepage begins to rapidly approach the maximum seepage for an infinitely deep water table[56]. Thus, if the water table is

Figure 8: Schematic of relation between seepage and depth to ground water



rather high and at some distance away from the stream less than two stream widths below the water surface of the stream, lowering the water table by ground-water pumping will "pull" more water from the stream. However, the water table at some distance is already more than two stream widths below the water level in the stream, further lowering of the ground-water table will not significantly increase the seepage, even when the ground-water table becomes "infinitely" deep!

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[54] The hydraulic connection between the stream and the water table is never broken – When $D_W = \infty$, the flow between the stream and the aquifer is strictly vertical, but always saturated or near saturated.

[55] The quantitative aspects of the relations shown in Figure 8 were developed solving the ground-water flow equations by numerical techniques – See Bouwer, H., Theory of Seepage from Open Channels, In: Advances in Hydroscience, Vol. 5, V.T. Chow (ed), Academic Press, New York, 121-172 (1969).

[56] See Bouwer, H., Surface Water-Groundwater Relations for Open Channels, Proc. Irrig. and Drain., Spcialty Conf., ASCE, Lincoln, Nebraska, pp. 149-156 (1988).

STREAMS WITH CLOGGING DEPOSITS

Cases I and II apply to clean streams (no clogging deposits of fine and/or organic materials with low hydraulic conductivity). These streams occur where flow velocities are rather high and sediment and organic growths cannot accumulate on the bottom[57]. Also, erosion and sedimentation may constantly rework the bottom and continuous deposits of fines cannot occur. Such deposits, however, can form in slow flowing streams. The resulting clogging layer then can have such a low hydraulic conductivity that it restricts seepage rates to values that are less than the saturated hydraulic conductivity of the underlying coarser materials (Case III, Figure 6). The aquifer below the clogging layer becomes unsaturated and gravity flow dominates. The underlying material then dries to a water content whereby the corresponding reduced hydraulic conductivity[58] is numerically equal to the seepage rate[59]. This seepage rate can be calculated by applying Darcy's[60] equation to the flow through the saturated clogging layer, knowing the thickness and hydraulic conductivity of this layer[61]. Some clogging layers are too thin (clay films or biofilms) to measure their thickness L and hydraulic conductivity K individually. In those cases, the ratio of thickness to hydraulic conductivity or hydraulic impedance (L/K) is used[62]. Sophocleous *et al.*[63] rank streambed clogging as the top factor in determining seepage losses.

The downward flow in the unsaturated zone between the stream and the water table is completely controlled by gravity, and the seepage rate is the same for a ground-water depth of 10 feet below the stream bottom with about 10 feet of unsaturated zone as for a ground-water depth of 100 feet below the stream with about 100 feet of unsaturated zone, or, for that matter, for an infinitely deep water table with an infinitely thick unsaturated zone! Ground-water depletion by pumping will then not significantly increase the seepage rate from the stream. To obtain unsaturated flow below the stream, the top of the capillary fringe above the water table must be below the stream bottom. The thickness of the capillary fringe may vary from 0.3 feet or less for coarse sandy and gravelly materials to about 1 foot for medium sands, 1.5 feet for silty or loamy sands, and 3 feet or more for loams and clays. Since most stream channels run in relatively coarse alluvium, it can be concluded that, for Case III, ground-water depletion by pumping of wells generally will not "pull" more water out of streams if the ground-water level is already deeper than about 3 feet below the stream bottom.

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[57] In effluent dominated streams, the biological clogging layers dominate the seepage processes and may occur even in high velocity streams.

[58] Hydraulic conductivity is a function of moisture content. The wetter the soil, the higher the hydraulic conductivity, and the drier the soil, the lower the hydraulic conductivity.

[59] If q_l if the seepage rate, h is the total head, ψ is the pressure head and z is the elevation head with $h = \psi + z$ then for unsaturated vertical flow, Darcy's law can be written, $q_l = -K(\psi)\, \partial h/\partial z = -K(\psi)\, (\partial \psi/\partial z + 1)$. For strictly gravity flow, $\partial\psi/\partial z = 0$, giving $q_l = -K(\psi)$ as stated.

[60] For saturated flow, the hydraulic conductivity is no longer a function of pressure head, ψ, and Darcy law for vertical flow is written $q_l = -K\, \partial h/\partial z$.

[61] See Bouwer, H., Theory of Seepage from Open Channels, In: Advances in Hydroscience, Vol. 5, V.T. Chow (ed), Academic Press, New York, 121-172 (1969); and Bouwer, H., Design Considerations for Earth Linings for Seepage Control, Ground Water, 20:531-537 (1982).

[62] *Id.*

[63] Sophocleous, M., A. Koussis, J.L. Martin, and S.P. Perkins, Evaluation of Simplified Stream-Aquifer Depletion Models for Water Right Administration. Ground Water 33:579-588 (1995).

For higher ground-water levels, Case III will become like Case I (Figure 4) if the ground-water level is above the water level in the stream. The clogging layer can then restrict the rate of ground-water flow into the stream. When the ground-water level drops, the rate of ground-water flow into the stream decreases linearly with D_W, until it becomes zero when $D_W = 0$. Further water level declines will then cause seepage from the stream to the aquifer and the stream will become "losing." Initially, this seepage will increase linearly with ground-water level drop until the top of the capillary fringe has dropped below the stream bottom and an unsaturated zone is created between the stream bottom and the capillary fringe. At this point, which is reached when the ground-water level has dropped to about 3 feet below the stream, seepage losses have reached maximum value and further lowering of ground-water levels will not increase seepage flows.

EPHEMERAL STREAMS

Many desert "washes" only flow when it rains and surface runoff is produced that enters rivulets and larger channels. Ground-water levels usually are well below such stream channels and seepage from the stream basically is a process of infiltration into dry soil material[64]. This infiltration causes a wetted zone below the channel with a downward moving wetting front that could reach ground water if the flow in the stream persists long enough. When it reaches the ground water, the seepage flow system could become of the Case II type and seepage rates could be reduced if ground-water levels are relatively high (D_w relatively small). If the ground water is too deep for Case II systems to develop, seepage or infiltration will not be affected by depth to ground water. When streamflow ceases, water from the upper 3 feet or so of wetted soil may evaporate[65]. Deeper water will evaporate much less and eventually may move to underlying ground water as unsaturated flow.

TRANSIENT SYSTEMS

It is often desirable to predict how ground-water pumping diminishes stream flow over time, starting with Case I, or with Cases II or III with initially small depths to ground water, so that ground-water level declines initially will diminish stream flow until the depth to ground water has become sufficiently large for stream seepage losses to essentially reach maximum values and further lowering of ground water will not "pull" more water out of the stream. A mathematical analysis of the transient situations for Case I was developed by Jenkins[66], who used the horizontal-flow assumption to predict the effect of continued pumping of one well on stream flow. This horizontal flow assumption, however, is valid only for shallow systems (shallow bedrock, thin aquifers, shallow ground water, and completely penetrating streams all the way down to bedrock or other lower boundary of the aquifer). The solution fails and begins to overestimate seepage where these conditions do not occur and vertical flow components in the underground system become significant. Furthermore, Jenkins' method is based on a single well-by-well analysis. In reality, pumped wells interact and interfere with each other, affect the regional properties as transmissivity and storativity, capture waters, and thus change the "bright

[64] See Bouwer, H., Groundwater Hydrology, McGraw-Hill, New York, N.Y., 480 pp. (1978).
[65] *Id.*
[66] See Jenkins, C.T., Techniques for Computing Rate and Volume of Stream Depletion by Wells, Ground Water, 6(2), Pp.37-46, (1968).

lines" with time. Modeling the system with a regional ground-water flow model[67] will then give more reliable results. By considering basin wide stream-aquifer interaction, numerical models are a valuable tool for addressing both legal and hydrologic questions. For example, when will a well begin to deplete a certain amount of appropriable water? Or, how much water is being pumped by a certain interest group for irrigation and how does this consumptive use affect other water users?

Regional ground-water flow models can closely emulate a real ground-water basin. With ample data and accurate calibration, these models can account for many of the complexities that are neglected by the simpler analytic models.

In a regional ground-water flow system, the water table is not horizontal. In the southwest, for example, ground water is recharged on the alluvial fans at the base of mountains and flows underground toward streams that meander along the valley floor. Such flow precludes horizontal water tables. Hydraulic parameters vary spatially throughout the regional flow system. Parameters such as transmissivity[68] or hydraulic conductivity and storativity[69] or specific yield[70] will vary spatially over the ground-water flow system. Furthermore, the regional ground-water flow system is likely to be composed of multiple layers of aquifers and not just a single layer.

The streams will only partially penetrate the aquifer and their streambed permeabilities will be subject to clogging over time. As water is extracted from a stream, its flow will decrease; and if too much water is extracted from the stream, the stream will dry up. Evapotranspiration will be a function of the depth to the water table—the higher the water table, the higher the evapotranspiration.

There will be multiple wells in a regional ground-water system and these wells will penetrate the flow system to different depths. Their pumping will produce additional vertical flow components within the ground-water system.

If both a predevelopment steady-state model and a transient-state model are developed, capture calculations can be performed by numerical models to determine the reduction of ground-water discharge to gaining streams, the increased recharge from losing streams, and the reduction of discharge to evapotranspiration from vegetation due to falling water tables.

All these activities can be performed with a regional ground-water model.

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[67]Regional ground-water flow models are numerical approximations models. Using numerical techniques, the field equations of the ground-water flow are approximated by a set of linear algebraic equations. There are computer packages available to aid in this process. One of the most frequently used package is called MODFLOW (See M.G. McDonald and Harbaugh, A.W., A Modular Three Dimensional Finite Difference Ground-water Flow Model, USGS, TWI 6-A1, 1988).

[68]Transmissivity is the product of the vertically averaged hydraulic conductivity times the saturated thickness of the aquifer.

[69]Storativity is the volume of water yielded per unit volume of underground material released by reduction of water compression and/or by increased compression of the porous material.

[70] Specific yield is the volume of water yielded per unit volume of underground material de-watered by ground-water pumping.

SUMMARY AND CONCLUSIONS

Confusion exists in legal, regulatory, and political circles as to how pumping of ground water and declining ground-water-levels affect stream flow in a surface water-ground-water continuum. Legal concepts such as "percolating water" and "underground streams", "subflow", and "bright lines" that separate the zone where wells pull significant amounts of water out of streams from zones where they pump mostly ground water, have no basis in hydrologic fact and are, therefore, impossible to administer. Hydrologically, stream-ground-water-well systems can be divided into gaining streams with ground-water tables above stream water levels and tributary ground water (Case I), losing perennial streams with ground-water tables below the water level in the stream and no clogging layer in the stream (Case II), losing perennial streams as in Case II but with a clogging layer on the stream wetted perimeter that controls stream seepage losses and causes underlying material to be unsaturated (Case III), and intermittent or ephemeral streams (Case IV). Lowering of ground-water levels due to pumping from wells or other causes will increasingly reduce streamflow for Case I where tributary ground-water flow will decrease in direct proportion to the decrease in slope of the ground-water table toward the stream. For Case II, lowering ground-water levels will increase stream seepage losses when depth to ground water is relatively small and flow in the aquifer is mostly lateral and controlled by the slope of the water table. As the ground-water level continues to drop, the seepage flow below the channel becomes more downward until eventually the seepage flow is gravity controlled and further lowering of ground-water levels will not significantly increase seepage losses. For shallow streams, this point is reached when the ground-water table at sufficient distance (ten stream widths) from the stream has dropped to a depth below the water level in the stream that is equal to about twice the width of the stream. For Case III, maximum seepage is already reached when the top of the capillary fringe is below the channel bottom. Normally, this is already achieved if the ground-water level is about 1.5 to 3 feet below the stream bottom. Further lowering of the ground-water level then will not increase seepage. Seepage from ephemeral streams is by infiltration during flow events and redistribution of water in the soil during periods of no flow. Unless the ground water is close to the stream bottom, its actual depth will not affect the seepage flow system and the stream losses. Thus, in general, continued pumping of ground water and lowering ground-water levels will increasingly reduce streamflows when initial ground-water levels are relatively high, but not when they are already low (more than two stream widths below clean streams and more than 1.5 to 3 feet below streams with a clogging layer on their perimeter). Nontechnical persons often find this difficult to understand. Where long-term effects of ground-water pumping must be quantified, the seepage flow systems must be analyzed as transient systems, which is best done with regional ground-water models that can include vertical flow components and can simulate the hydrologeologic setting of the situation in all its major complexities, including effects of ground-water pumping on ground-water recharge and discharge on a basin-wide scale, and on capture of water by aquifers.

Once the effects of ground-water pumping on streamflow have been quantified, the legal profession, in close cooperation with hydrologists, can then decide how to best solve conflicting water uses and the situation as a whole. If continued ground-water pumping continues to decrease streamflow and jeopardizes holders of surface water (appropriable water) rights, who should give? Should ground-water users reduce pumping their wells, should surface water users reduce their diversions of stream water, or both, and by how much? What are the long-term aspects (ground-water depletion cannot go on forever)? Should surface water users augment their diversions with ground water? Should broader solutions be considered and implemented, such as water marketing, importing water, cloud seeding, water reuse, more surface (dams) and underground (artificial recharge) storage of water, and other aspects of "integrated" water resources management? How should environmental effects such as reduction or loss of streamflow, aquatic life, riparian habitats, and scenic and recreational values be mitigated? Can sustainable solutions be achieved?

Water resource problems and conflicts between surface and ground-water users require interdisciplinary action to obtain solutions. Legal maneuvering and creation of hydrologic absurdities are not the answer; they simply will not hold water. Finally, litigation is slow and expensive and, unfortunately, does not create any extra water.